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Ecosystem dynamics and management in relation to conservation in forest systems

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Abstract

Any system of conservation reserves sits within the context of the surrounding ecosystem. Modifications to this surrounding matrix will inevitably have some impact on the reserve system. While forest ecosystems in south-western Australia are significantly less modified than other ecosystems, particularly in the agricultural area, they are nevertheless subjected to marked human-induced modifications. These take the form of forest management practices including timber harvesting and fuel reduction burning, and the impacts of introduced species including the pathogen *Phytophthora cinnamomi*. The level of information available to assess the impacts of these modifications is for the most part inadequate. Changing ideas on the nature and dynamics of ecosystems require a reappraisal of how we manage ecosystems for conservation and production purposes. The recognition of interconnections between different impacts and between different ecosystem components has resulted in the development of the concept of "ecosystem management". This aims to integrate the various management goals and allow production to take place in such a way that both the long term productive potential and the biodiversity of the forest are maintained.

Introduction

While there is currently considerable debate over the selection of reserves within forests in Australia, less attention has been paid to how these reserves are likely to fare within the context of the forest ecosystem as a whole. I argue here that conservation reserves do not form discrete entities which can be considered and managed separately from the rest of the forest. Rather, the whole forest has to be considered as a collection of interacting parcels of land, and events in one parcel are liable to impact those in surrounding areas. This has three major implications. Firstly, reserves must be managed not only to meet the needs of the biota being conserved, but also in the context of the main ecosystem processes prevailing in the forest. Secondly, the impacts of management activities in the forest as a whole have to be assessed. Finally, the interconnected nature of natural systems means that the forest as a whole, including those areas outside conservation reserves, plays a vital role in the overall conservation of biodiversity. I explore these points in this paper, and discuss their implications for forest management, with particular reference to Western Australia.

Ecosystem dynamics

The forest ecosystem consists of the forest biota and its environment (Fig 1). The biotic components are divided up according to their primary functions (*i.e.* primary producers, consumers, decomposers *etc.*). These, and other non-living components (dead organic matter, inorganic material) form pools within which carbon, other nutrients, water and other important elements accumulate. Ecosystem dynamics describe the flows of energy and elements into and out of the system, and between the various pools (*e.g.* Waring & Schlesinger 1985; Aber & Melillo 1991). In addition, the responses to, and recovery from, disturbance form a further important set of ecosystem dynamics, incorporating the ideas of succession and resilience.

Ecosystem processes have frequently been ignored in conservation management, presumably because conservation has been primarily directed at species and biotic communities. Ecosystem ecology has largely developed separately from population and community ecology, and has tended to subsume biotic components into larger "black boxes" (Aber & Melillo 1991), as illustrated in Figure 1. While population and community

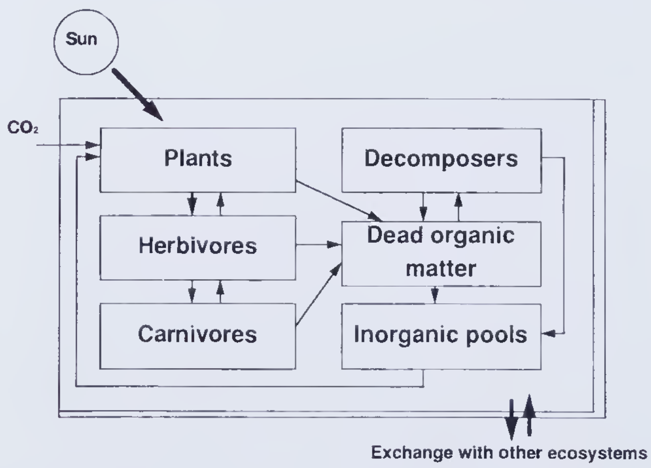

Figure 1. A simplified representation of an ecosystem, indicating the major pools and flows of carbon and nutrients.

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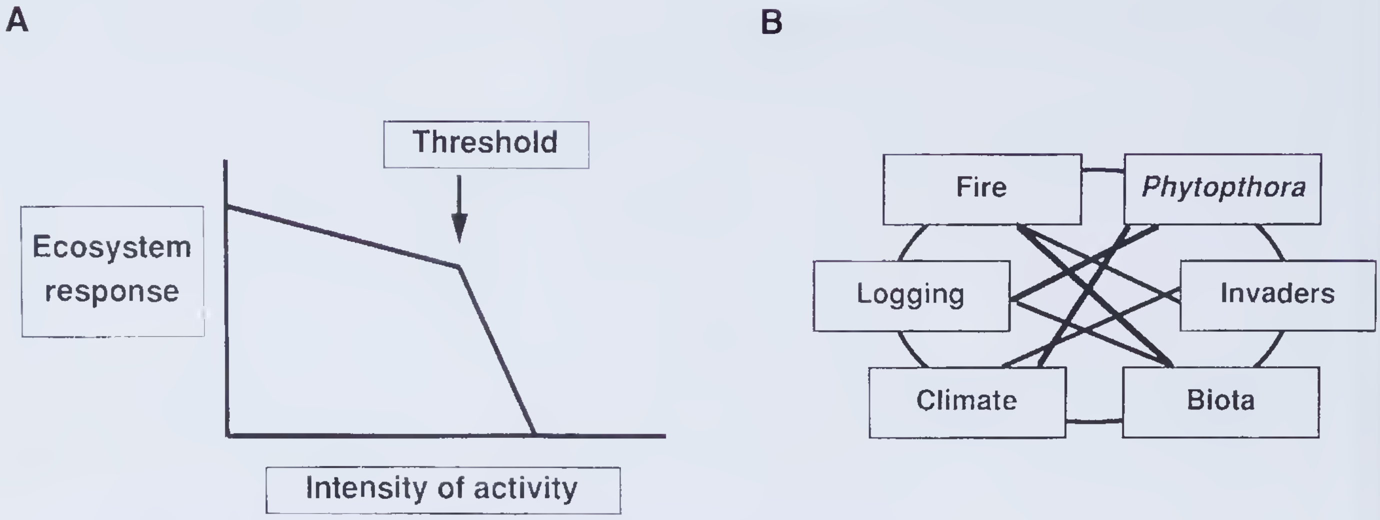

Figure 2. Characteristics of complex ecosystems which render the search for simple cause and effect relationships difficult. A Non-linear system response to human activities. The system may show little or no response until a certain level of impact is experienced, at which stage a sudden system change occurs. B Complex interactions between system components and human activities. The diagram shows the main factors discussed for Western Australian forest, and potential linkages between them.

ecology have been concerned with entities such as species and populations, ecosystem ecology is concerned with the flows of materials between components - what Pickett *et al.* (1994) have termed the "things versus stuff" dichotomy. However, it is increasingly recognized that the links between species and ecosystems are important, and attempts are now being made to integrate the two streams of ecology (Pickett *et al.* 1994; Jones & Lawton 1995).

In forest systems of Western Australia, the major ecosystem dynamics to be considered include the natural dynamics of the forest, and a set of dynamics imposed by humans. Here, natural forest dynamics are determined largely by three factors which predominate in the area *i.e.* a mediterranean-type climate, with its well-defined summer drought; soils with low nutrient status; and the incidence of fire and other disturbances. These factors, and ecosystem responses to them, have been considered in detail elsewhere (Kruger *et al.* 1983; Dell *et al.* 1986; Dell *et al.* 1989; Davis & Richardson 1995), and I will not dwell on them here. Rather, I will concentrate on the set of imposed dynamics. The most

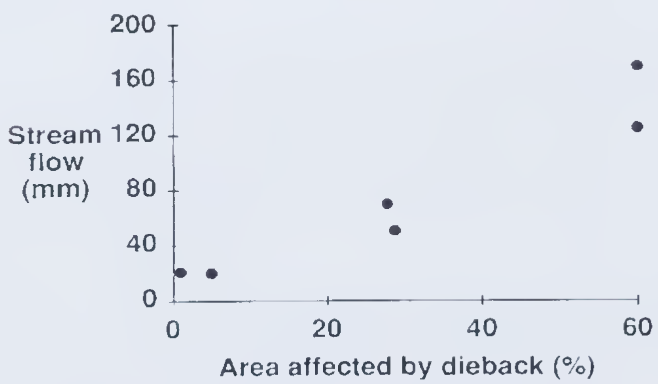

Figure 3. Streamflow in catchments with different proportions affected by *Phytophthora cinnamomi* (redrawn from Schofield *et al.* 1989).

important of these are forest management practices, in particular timber harvesting and fuel reduction burning, and the impacts of invasive species, including the introduced pathogen, *Phytophthora cinnamomi.*

Introduced species

Phytophthora cinnamomi is undoubtedly a major factor influencing the forest ecosystem in Western Australia and in other parts of the country (Dell & Malajczuk 1989). A recent symposium has highlighted the impacts of the disease on a variety of forest components (Withers *et al.* 1994). From an ecosystem perspective, the disease is important because of its impacts on forest structure and composition and resulting environmental changes. Depending on the severity of attack, *Phytophthora* causes the loss of overstorey and understorey plant species, which then presumably alters the microclimate and reduces evapotranspiration. This in turn leads to increased input of water to the system, which has been recorded as increasing stream flows with increasing degrees of dieback incidence (Fig 3; Schofield *et al.* 1989). This change in local hydrology could potentially lead to localized vegetation change (Davidson 1994), but this has not been investigated in detail.

Introduced predators, particularly foxes and cats, are thought to be one of the major causal factors leading to the complete or near extinction of many Australian marsupials (Burbidge & McKenzie 1989; Friend 1990). Indeed, Western Australian forests have provided the last refuge for a number of species, presumably because fox numbers remained lower than in other areas, and/or they arrived later. Predator control is now practiced in many areas, with obvious success indicated by increases in abundances of native mammals (Kinnear *et al.* 1988; Friend 1990). Changes in abundances of mammals in ecosystems are liable to have impacts on other system components due to their herbivory, digging activities and dispersal of fungal spores (Lamont *et al.* 1985; Noble 1993; Lamont 1995). Such interactions and their disruption may have important, but difficult to detect, effects on ecosystem function (Hobbs *et al.* 1995).

Invasive plants are another major threat to many ecosystems across Australia (Humphries *et al.* 1991; Humphries 1993). Individual invaders, such as bridal creeper (*Myrsiphyllum asparagoides*), have the potential to crowd out native species and alter vegetation composition and structure. Herbaceous species, especially grasses, also have the potential to alter fire regimes by changing the structure and availability of fuel (D'Antonio & Vitousek 1992). In the region of 1500 species are currently naturalized across Australia, with 1032 species recorded from Western Australia (Keighery 1995). Two hundred and twenty species are recognized as noxious weeds across Australia (Parsons & Cuthbertson 1992), and many are problems in native ecosystems. In addition to existing problems, there are likely to be many more species which could become a problem in the future (Hobbs 1993a). These include, for instance, pine species planted in native forest areas which have been found to be invasive elsewhere in the world (Richardson *et al.* 1994). Australia continues to import plant species without due consideration for the potential threats of invasiveness. There is a clear need for an integrated approach to weed management in the forests and elsewhere (Hobbs & Humphries 1995).

Forest management practices

Opinions vary as to the extent to which current forest management practices affect ecosystem processes (Abbott & Christensen 1994; Calver *et al.* 1996). A repeated assertion is that there is no evidence to show that the ecological processes that maintain the forests have been impaired or that forest biodiversity is impacted by forest management (Abbott & Christensen 1994; Anon 1994). However, this may be partially due to the lack of monitoring and research into such potential impacts. In most parts of Australia, little research work has been conducted into the long-term impacts of timber or burning operations. The impact of disturbance-causing activities concentrates on individual species, and no long term monitoring has been implemented, apparently because it is "very difficult" (Anon 1994, p52).

This then leads to a dearth of information with which to assess statements on the impacts of management operations. For instance, Schofield *et al.* (1989) stated that "*No long term detailed studies on the effects of different silvicultural systems on the hydrology of the jarrah forest have been carried out*". This situation is being redressed (Stoneman 1993), and some information is available from other studies. These indicate that timber harvesting can lead to increases in streamflow over a period of years. Streamflow increases of 91-182% were reported by Borg *et al.* (1987) following heavy logging, and Bari *et al.* (1994) have shown marked increases in streamflow and groundwater discharge following clear felling. These impacts were highest immediately after logging, but persisted for at least 8 years. These findings concur with experimental work carried out elsewhere (Bormann & Likens 1981).

Impacts of logging on other system components are equally poorly documented. What, for instance, are the impacts of timber harvesting on the nutrient pools in the forest? There are indications from forests elsewhere that impacts on soil properties can be substantial (Rab 1994). While findings from one forest type are not necessarily directly applicable to another, such results indicate that efforts should be made to assess possible impacts in Western Australian forests. Considerable effort has been expended in Tasmania, for instance, in assessing impacts of logging systems on system components (*e.g.* Hickey 1994; Taylor & Haseler 1995) and clear recognition of the need to consider impacts of management on biodiversity are evident in management manuals (Taylor 1991; Anon 1993; Duncan & Packham 1994; Jackson & Taylor 1994). Little of this type of assessment has been carried out in Western Australia. Work by Mawson & Long (1994) has suggested that current logging practices significantly alter habitat suitability for some bird species, although the validity of the methods used has been questioned by Burrows *et al.* (1995). Similar discussions on the impacts of logging have occurred in Victoria, where Attiwill (1994a,b) has implied that logging is in many ways equivalent to natural forest disturbance, a conclusion which has been contested (Lindenmayer 1995; see also subsequent response by Attiwill 1995).

A similar story is apparent when the impacts of fire management are examined (Williams & Gill 1995). The jarrah forest is currently subjected to widespread short-rotation fuel reduction burning, which has been developed to reduce the risk of destructive wildfires. Controversy surrounds the questions of whether such a burning regime is effective and whether it has adverse impacts on the forest ecosystem (McGrath 1985; Tingay 1985; Underwood *et al.* 1985). It has been claimed that the current regime mimics the regime prevailing prior to European settlement (Burrows *et al.* 1995), although the evidence for this is not compelling. Burrows *et al.* (1995) state that fire scars on *Eucalyptus marginata* trees indicate the occurrence of moderate to severe fires in the forest occurred with a mean interval of 81 years. They then use historical accounts of aboriginal burning and lightning records to conclude that these severe fires must have been accompanied by low intensity fires every 2-5 years. The question remains as to whether such a regime of low intensity fires prevailed over the whole forest or was restricted to areas most frequented by aborigines. If it prevailed over the whole forest, this then suggests that high intensity fires are possible even under a regime of fuel reduction burning, as currently practiced. Indeed, observations in other forest systems suggests that intensive fuel reduction measures do not necessarily "fire proof" forests (DellaSala *et al.* 1995).

Abbott & Christensen (1994) suggest that the current fire regime (and logging activities) are "*....a minor, irregular and relatively insignificant perturbation...*". On the other hand, McCaw & Burrows (1989) conclude that "*While many studies have examined the effects of one, or occasionally several fires, on plant and animal communities in the forest, the basis for predicting longer term effects of different fire regimes is limited*". Indeed, the impact of one fire may be minimal, although even this conclusion is open to question (*e.g.* Majer & Abbott 1989). Again, evidence from Victoria points to a potentially detrimental impact of fuel reduction burning (Hamilton *et al.* 1991), although the conclusions of this study again have been questioned (McCaw 1993). Nevertheless, it is the overall fire regime (*i.e.* frequency, intensity, season, size *etc.*) which shapes the vegetation in the long term, and long-term data on vegetation changes under current fire management practices are not available.

Analyses such as that by Abbott & Christensen (1994) look at relatively short time scales and suggest no significant ecosystem changes. For instance, the present fuel reduction fire regime has been in place for less than 40 years, a short time span in terms of forest dynamics. Longer term impacts could be significant, but will not be noticed if relevant monitoring systems are not in place. Even if impacts are detected, it could be some considerable time before a policy or management response is implimented. A clear example of the types of lag involved in responding to problems is the salination of agricultural land caused by past land clearance. This problem was first documented in the 1920s (Wood 1924) but is only now being acted on at the policy level.

Complexity and non-linearity

The degree of debate over the importance of changes to forest ecosystems arising from management practices indicates the difficulty in reaching conclusions on the issue. The problem is further compounded by two characteristics of natural systems. The first is the likelihood that system components exhibit non-linear responses to particular activities (Fig 2A). In other words, the system may change unpredictably or may show relatively little change in response as the intensity of an activity increases, until a threshold level is reached, at which point system behavior changes dramatically. Alternatively, the system may show no response to a particular activity for a period of time, and then change rapidly. Such non-linear behaviour is a recognized characteristic of complex systems (*e.g.* Roberts 1994).

The second characteristic is the complexity of interactions between system components and processes (Fig 2B). This may be referred to as the "ECWEE" principle *i.e.* "everything is connected with everything else" (see Oppenheimer 1995). While this may be an over-generalization, it is nevertheless the case that complex interactions and feedback loops are common in natural systems. Classical scientific approaches to environmental questions attempt to deny the importance of these interconnections since they render the search for simple cause-and-effect relationships almost impossible. Certainly, much can still be gained by single factor studies, but failure to recognize the potential for complex interactions between factors can also lead to simplistic and misleading conclusions. For instance, while there has been a considerable body of research on the various individual components in Figure 2B, the possible interactions have received little attention. Are there, for example, interactions between the effects of forest management and the spread of *Phytophthora*?

An important part of the problem, however, lies in the continued assertion that current management practices are having little or no impact, even in the absence of data (Abbott &Christensen 1994). It is clear that all management has some impact on the ecosystem (even if the management is to do nothing). The

Figure 4. North Bungulla nature reserve in the Western Australian wheatbelt, illustrating the location of the reserve within a greatly-modified agricultural matrix. Although less obvious, forest reserves also sit within an altered matrix. (Photograph by Dion Steven).

important question is whether the level of impact is acceptable or not. The acceptability or otherwise of any particular impact will change as society's expectations and priorities change. It is clear that forest managers need to be responsive to such changes (Gordon 1994). However, the acceptability of the level of impact can be assessed only if the relevant information is available. In 1977, the Senate Standing Committee on Science and the Environment (Anon 1977) stated that "*the extreme lack of knowledge on the biological sphere......is hampering responsible decision making*". In 1993, the Resource Assessment Commission (Anon 1993) still had to conclude that "*the level of information on impacts appears insufficient for most current uses*". This is echoed internationally by the US National Research Council (Anon 1990), which concluded that "*.. the existing level of knowledge is inadequate to develop sound management practices*". Obtaining this knowledge for Western Australian forests is problematic in the face of current underfunding for research within state agencies and in an environment which is not conducive to open scientific debate on forest issues.

Ecosystem management

How is all this relevant to the selection and management of conservation reserves? Surely it could be argued that impacts in the parts of the forest managed for production are irrelevant if adequate areas are set aside for conservation? Unfortunately, it is becoming increasingly recognized that this is not the case, and that conservation management and production management have to be integrated to achieve the goal of sustainability. Biota and ecosystem processes do not respect legal boundaries (Newmark 1985), and different parts of the landscape interact. Reserves are located within a surrounding altered or managed matrix. This dichotomy between reserve and matrix is obvious in cases where the matrix is noticeably altered, for instance in an agricultural situation (Fig 4). In these situations, there are clear impacts of the surrounding matrix on the remnant vegetation within reserves (Saunders *et al.* 1991; Hobbs 1993b; Hobbs 1994). In the case of forests, the impacts are less obvious, because forestry operations do not necessarily create an entirely transformed matrix. Nevertheless, modifications outside reserves can have impacts within the reserves, and reserves are not immune from factors arising in the surrounding matrix, such as dieback, fire, feral animals and so on.

At the same time, it is also becoming recognized that reserve systems will not be sufficient on their own to conserve the biodiversity of a region, and that conservation and production management have to be integrated to achieve the goals of sustainability and conservation. For instance, Sample *et al.* (1993) suggest that "*Many ecologists agree that neither our current system of forest reserves... nor any conceivable such system will be sufficient to provide adequate protection of biodiversity*". They continue, "*We are urged .. to consider all lands within the ecosystem as important to its overall functioning and sustainability*". Further, they suggest, "*We are also urged...to discover ways in which the protection of biodiversity ... can be thoroughly incorporated into the management of lands for a variety of uses and values*". In other words, we need to ensure that the areas set aside for conservation sit in a matrix which is managed in a way which ensures the continued integrity of the reserves and provides some conservation benefit as well as productive outputs. This includes forests both on public and private land, especially where private holdings constitute a relatively large component of the conservation and production resource (*e.g.* Braithwaite *et al.* 1993). Attempts to develop this approach are being made in many different types of forest (*e.g.* Hansen *et al.* 1991; Caraher & Knapp 1995; Frumhaff 1995).

Such a suggestion could be viewed as an attempt by those interested in conservation to grab as much of the forest as possible and prevent further productive use. On the other hand, it seems likely that continued productive output also strongly depends on the maintenance of healthy, functioning forest ecosystems. The challenge is to find management regimes that optimize both conservation and production and retain the functionality of the ecosystem. Is this a pipe dream? A suggested approach to these challenges is what has been termed "ecosystem management". This approach to management tries to develop a holistic framework and move away from the fragmented and frequently contradictory practices conducted in parts of the forest managed for different goals. Ecosystem management recognizes that a variety of scales are important in management, from the individual site to the landscape and regional scale, and that management needs to be coordinated across these scales (Franklin 1993; Salwasser *et al.* 1993). Ecosystem management also recognizes a key set of ecosystem characteristics, outlined by Costanza (1992), Norton (1992) and Grumbine (1994) :

1. *Dynamism*. The classical idea of the "balance of nature" is being replaced by the concept of the "flux of nature"; *i.e.* ecosystems are constantly changing and should not be regarded as static entities (Botkin 1990; Pickett *et al.* 1992);
2. *Relatedness*. The "ECWEE" principle discussed above, and the need for cross-boundary management;
3. *Hierarchy*. The idea that natural systems and processes are nested, and the importance of managing at the right scales and recognizing connections between scales;
4. *Creativity and ecological integrity*. Natural systems are self-organizing, and the processes which maintain this organization need to be maintained; and
5. *Differential fragility*. Systems vary in their resilience and thus have to be managed accordingly, as no one prescription will be suitable across a range of ecosystems.

Gordon (1994) and Grumbine (1994) suggested the following principles of ecosystem management:

1. *Manage where you are*. Emphasis on site-specific properties, and the objectives of the management;
2. *Manage with people in mind*. Management needs to consider human desires, influences and responsibilities. Human values play a dominant role in determining management goals. In addition, Sample *et al.* (1993) suggest, "*An ecosystem ap-*

proach must be not only ecologically sound but also economically viable and socially responsible" and *"A focus on biophysical factors, with little or no consideration of social and economic needs, is doomed from the start"*. Magerum & Born (1995) also point to interaction with stakeholders and the public as a key operational component for integrated management;

3. *Manage across boundaries.* The recognition and management of neighbouring influences, and integration of management goals through interagency cooperation. Decision support systems and allocation modelling procedures can be used to facilitate this (*e.g.* Ive & Cocks 1989; Kilgour & Lau 1994)
4. *Manage based on mechanisms rather than "rules of thumb"*. Use existing knowledge on processes and interactions, and seek to improve this knowledge. Assume that current knowledge is provisional and be prepared to adapt management practices in the light of new information; and
5. *Manage without externalities.* Include all known components and interactions when management decisions are made.

The goal of ecosystem management, according to Gordon (1994), is a *"sustained forest"*, which exhibits a *"full range of characteristics and organisms, not just a sustained supply of wood"*. Achieving this will not necessarily be easy. There will undoubtedly be problems with definitions and operationalising these definitions (*e.g.* Burroughs & Clark 1995). The whole concept of ecosystem management requires detailed knowledge of ecosystem processes and often, as discussed above, this knowledge is lacking. This lack of knowledge cannot, however, be used as an excuse or rationale for inaction or for ceasing current practices. Rather, management practices need to be adaptive and experimental, and adequately monitored. Changes in practice should be implimented as more and better information becomes available. However, current management philosophies and structures are not necessarily malleable enough to incorporate the necessary changes in approach. For instance, Sample *et al.* (1993) have suggested that *"Another challenge is the reorganization of resource-managing organizations, both public and private, away from function-based, target oriented hierarchies towards open organizations conducive to multidisciplinary approaches to achieving desired future resource conditions"*.

This problem has been discussed more generally by Holling (1995), who suggests that *"The very success of managing a target variable for sustained production of food or fiber apparently leads inevitably to an ultimate pathology of less resilient and more vulnerable ecosystems, more rigid and unresponsive management agencies, and more dependent societies"* He sees the underlying causes of this to be the prevalence of a single target and a piece-meal policy, a single scale of focus (typically on the short term and the local), no realization that all policies are experimental, and rigid management with no priority to design interventions as ways to test hypotheses underlying policies. An obvious corollary is that the way to deal with the problem is to reverse these causes, and to develop an integrated cross-scale management policy and an adaptive management strategy which monitors the impacts of management activities and modifies the regime where necessary (Gunderson *et al.* 1995).

Conclusions

The selection and design of nature reserves and reserve systems is but one part of the strategy required for adequate protection and maintenance of biodiversity in forest ecosystems (or any other type of ecosystem). Reserves sit within a matrix of lands managed for purposes other than nature conservation. While they may be treated as separate legal or administrative entities, they are not separate in ecosystem terms. Ecosystem flows ensure that reserve systems are connected to the surrounding matrix, and the integrity of the reserves is in large measure dependent on what happens in that matrix. The best reserve system in the world will not do what it is supposed to do in the long term if the surrounding matrix is degrading. The surrounding matrix of production lands thus plays a part in maintaining the biodiversity of a region. We thus need to move away from a piece-meal approach to management in which conservation and production management are considered separately. Management goals are now much more complex than previously and aim to maintain not only a sustainable harvest of timber, but also the structure and complexity of the forest ecosystem. The concept of ecosystem management aims to integrate the various management goals and allow production to take place in such a way that both the long term productive potential and the biodiversity of the forest are maintained. The challenge is to make the concept operational and to convince everyone involved of the urgent need to do so.

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References

Abbott I & Christensen P 1994 Application of ecological and evolutionary principles to forest management in Western Australia. Australian Forestry 57:109-122.

Aber J D & Melillo J M 1991 Terrestrial Ecosystems. Saunders College Publishing, Philadelphia.

Anon 1977 Woodchips and the Environment. Senate Standing Committee on Science and the Environment. Australian Government Printing Service, Canberra.

Anon 1990 Forestry Research: A Mandate for Change. National Research Council. National Academy Press, Washington, DC.

Anon 1993 Ecological Impacts of Forest Use: A Survey of Completed Research. Resource Assessment Commission Research Paper 9. Australian Government Printing Service, Canberra.

Anon 1994 Forest Management Plan 1994-2003. Department of Conservation and Land Management, Perth.

Attiwill P M 1994a The disturbance of forest ecosystems: the ecological basis for conservative management. Forest Ecology and Management 63:247-300.

Attiwill P M 1994b Ecological disturbance and the conservative management of eucalypt forests in Australia. Forest Ecology and Management 63:301-346.

Attiwill P M 1995 Managing Leadbeater's possum in the mountain ash forests of Victoria - reply. Forest Ecology and Management 74:233-237.

Bari M A, Smith N J, Boyd D W & Ruprecht J K 1994 Generation of streamflow following clearfell logging and regeneration at March Road catchment. Report WS119. Water Authority of Western Australia, Perth.

Borg H, King P D & Loh I C 1987 Stream and ground water response to logging and subsequent regeneration in the southern forest of Western Australia. Interim results from paired catchment studies. Surface Water Branch, Water Authority of Western Australia. Report WH 34. Water Authority of Western Australia, Perth.

Bormann F H & Likens G E 1981 Pattern and Process in a Forested Ecosystem. Springer-Verlag, New York.

Botkin D B 1990 Discordant Harmonies. A New Ecology for the Twenty-first Century. Oxford University Press, Oxford.

Braithwaite W, Belbin L, Ive J & Austin M 1993 Landuse allocation and biological conservation in the Batemans Bay forests of New South Wales. Australian Forestry 56:4-21.

Burbidge A A & McKenzie N L 1989 Patterns in the modern decline of Western Australia's vertebrate fauna: causes and conservation implications. Biological Conservation 50:143-198.

Burroughs R H & Clark T W 1995 Ecosystem management: a comparison of Greater Yellowstone and Georges Bank. Environmental Management 19:649-663.

Burrows N D, Ward B & Robinson A D 1995 Jarrah forest fire history from stem analysis and anthropological evidence. Australian Forestry 58:7-16.

Calver M C, Hobbs R J, Horwitz P & Main A R 1996 Science, principles and forest management: a response to Abbott and Christensen. Australian Forestry 59:1-6.

Caraher D & Knapp W H 1995 Assessing ecosystem health in the Blue Mountains. In: Silviculture: From the Cradle of Forestry to Ecosystem Management. Southeast Forest Experiment Station General Technical Report SE-88. United States Department of Agriculture, Forest Service, Hendersonville, North Carolina, 34-41.

Costanza R 1992 Toward an operational definition of ecosystem health. In: Ecosystem Health: New Goals for Environmental Management (ed R Costanza, B G Norton & B D Haskell). Island Press, Washington, DC, 239-256.

D'Antonio C M & Vitousek P M 1992 Biological invasions by exotic grasses: the grass/fire cycle, and global change. Annual Review of Ecology and Systematics 23:68-87.

Davidson E M 1994 Role of environment in dieback of jarrah: effects of waterlogging on jarrah and *Phytophthora cinnamomi* and infection of jarrah by *P. cinnamomi*. Journal of the Royal Society of Western Australia 77:123-126.

Davis G W & Richardson D M 1995 Mediterranean-type Ecosystems: The Function of Biodiversity. Springer, New York.

Dell B, Havel J J & Malajczuk N, ed 1989 The Jarrah Forest: A Complex Mediterranean Ecosystem. Kluwer, Dordrecht.

Dell B, Hopkins A J M & Lamont B B 1986 Resilience in Mediterranean-type Ecosystems. Junk, The Hague.

Dell B & Malajczuk N 1989 Jarrah dieback - a disease caused by *Phytopthora cinammomi*. In: The Jarrah Forest: A Complex Mediterranean Ecosystem (ed B Dell, J J Havel & N Malajczuk). Kluwer, Dordrecht, 67-87.

DellaSala D A, Olson D M, Barth S E, Crane S L & Primm S A 1995 Forest health: moving beyond rhetoric to restore healthy landscapes in the inland Northwest. Wildlife Society Bulletin 23:346-356.

Duncan F & Packham J 1994 Forest Botany Manual. Nature Conservation Region 9. Forestry Commission, Hobart.

Franklin J F 1993 The fundamentals of ecosystem management with applications in the Pacific Northwest. In: Defining Sustainable Forestry (ed G H Aplet, N Johnson, J T Olson & V A Sample). Island Press, Washington DC, 127-144.

Friend J A 1990 The numbat *Myrmecobius fasciatus* (Myrmecobiidae): History of decline and potential for recovery. Proceedings of the Ecological Society of Australia 16:369-377.

Frumhaff P C 1995 Conserving wildlife in tropical forests managed for timber: to provide a more viable complement to protected areas. BioScience 45:456-464.

Gordon J C 1994 From vision to policy: a role for foresters. Journal of Forestry 92:16-19.

Grumbine R E 1994 What is ecosystem management? Conservation Biology 8:27-38.

Gunderson L H, Holling C S & Light S S 1995 Barriers broken and bridges built: a synthesis. In: Barriers and Bridges to the Renewal of Ecosystems and Institutions (eds L H Gunderson, C S Holling & S S Light). Columbia University Press, New York, 489-532.

Hamilton S D, Lawrie A C, Hopmans P & Leonard B V 1991 Effects of fuel-reduction burning on a *Eucalyptus obliqua* forest ecosystem in Victoria. Australian Journal of Botany 39:203-217.

Hansen A J, Spies T A, Swanson F J & Ohmann J L 1991 Conserving biodiversity in managed forests: lessons from natural forests. BioScience 41:382-392.

Hickey J E 1994 A floristic comparison of vascular species in Tasmanian oldgrowth mixed forest with regeneration resulting from logging and wildfire. Australian Journal of Botany 42:383-404.

Hobbs R J 1993a Dynamics of weed invasion: implications for control. In: Proceedings of the 10th Australian Weeds Conference and 14th Asian Pacific Weed Society Conference. Vol. 1. Weed Society of Queensland, Brisbane, 461-465.

Hobbs R J 1993b Effects of landscape fragmentation on ecosystem processes in the Western Australian wheatbelt. Biological Conservation 64:193-201.

Hobbs R J 1994 Fragmentation in the wheatbelt of Western Australia: landscape scale problems and solutions. In: Fragmentation in Agricultural Landscapes (ed J Dover). IALE, Garstang, UK, 3-20.

Hobbs R J, Groves R H, Hopper S D, Lambeck R J, Lamont B B, Lavorel S, Main A R, Majer J D & Saunders D A 1995 Function of biodiversity in the mediterranean-type ecosystems of southwestern Australia. In: Mediterranean-type Ecosystems: The Function of Biodiversity (eds G W Davis & D M Richardson). Springer, New York, 233-284.

Hobbs R J & Humphries S E 1995 An integrated approcah to the ecology and management of plant invasions. Conservation Biology 9:761-770.

Holling C S 1995 What barriers? What bridges? In: Barriers and Bridges to the Renewal of Ecosystems and Institutions (ed L H Gunderson, C S Holling & S S Light). Columbia University Press, New York, 3-34.

Humphries S E 1993 Environmental impact of weeds. In: Proceedings of the 10th Australian Weeds Conference and 14th Asian Pacific Weed Society Conference. Vol 2. Weed Society of Queensland, Brisbane, 1-11.

Humphries S E, Groves R H & Mitchell D S 1991 Plant invasions of Australian ecosystems. A status review and management directions. In: Kowari 2. Plant invasions. The incidence of environmental weeds in Australia. Australian National Parks and Wildlife Service, Canberra, 1-127.

Ive J R & Cocks K D 1989 Incorporating multiparty preferences into land-use planning. Environment and Planning B: Planning and Design 16:99-109.

Jackson J & Taylor R 1994 Threatened Fauna Manual for Production Forests in Tasmania. Forestry Commission, Hobart.

Jones C G & Lawton J H 1995 Linking Species and Ecosystems. Chapman and Hall, New York.

Keighery G J 1995 How many weeds? In: Invasive weeds and regenerating ecosystems in Western Australia (ed G Burke). Institute for Science and Technology Policy, Murdoch University, Perth,

Kilgour B & Lau A 1994 Decision support systems for Victorian forests - future durections using GIS. In: Resource Technology '94 Conference Proceedings: New Opportunities - Best Practice (ed I Bishop). University of Melbourne, Parkville, 199-206.

Kinnear J E, Onus M L & Bromilow R N 1988 Fox control and rock wallaby population dynamics. Australian Wildlife Research 15:435-450.

Kruger F J, Mitchell D T & Jarvis J U M 1983 Mediterranean-type Ecosystems: The Role of Nutrients. Springer, New York.

Lamont B B 1995 Interdependence of woody plants, higher fungi and small marsupials in the context of fire. CALMScience Supplement 4:151-158.

Lamont B B, Ralph C S & Christensen P E 1985 Mycophagous marsupials as dispersal agents for ectomycorrhizal fungi on *Eucalyptus calophylla* and *Gastrolobium bilobum*. New Phytologist 101:651-656.

Lindenmayer D B 1995 Forest disturbance, forest wildlife conservation and the conservative basis for forest management in the mountain ash forests of Victoria - comment. Forest Ecology and Management 74:223-231.

Magerum R D & Born S M 1995 Integrated environmental management: moving from theory to practice. Journal of Environmental Planning and Management 38:371-391.

Majer J D & Abbott I 1989 Invertebrates of the jarrah forest. In: The Jarrah Forest: A Complex Mediterranean Ecosystem (ed B Dell, J J Havel & N Malajczuk). Kluwer, Dordrecht, 111-122.

Mawson P R & Long J L 1994 Size and age parameters of nest trees used by four species of parrot and one species of cockatoo in south-west Australia. Emu 94:149-155.

McCaw W L 1993 Effects of fuel-reduction burning on a *Eucalyptus obliqua* forest ecosystem in Victoria. Comment and Response. Australian Journal of Botany 41:413-414.

McCaw W L & Burrows N D 1989 Fire management. In: The Jarrah Forest: A Complex Mediterranean Ecosystem (ed B Dell, J J Havel & N Malajczuk). Kluwer, Dordrecht, 317-334.

McGrath M 1985 Fire planning and management: an overview. In: Fire Ecology and Management in Western Australian Ecosystems (ed J W Ford). WAIT Environmental Studies Group, Perth, Western Australia, 219-221.

Newmark W D 1985 Legal and biotic boundaries of western North American national parks, a problem of congruence. Biological Conservation 33:197-208.

Noble J C 1993 Relict surface-soil features on semi-arid mulga (*Acacia aneura*) woodlands. Rangelands Journal 15:48-70.

Norton B G 1992 A new paradigm for environmental management. In: Ecosystem Health: New Goals for Environmental Management (ed R Costanza, B G Norton & B D Haskell). Island Press, Washington, DC, 23-41.

Oppenheimer M 1995 Context, connection and opportunity in environmental problem solving. Environment 37:10-15, 34.

Parsons W T & Cuthbertson E G 1992 Noxious weeds of Australia. Inkata Press, Melbourne.

Pickett S T A, Kolasa J & Jones C G 1994 Ecological Understanding: The Nature of Theory and the Theory of Nature. Academic Press, New York.

Pickett S T A, Parker V T & Fielder P 1992 The new paradigm in ecology: implications for conservation biology above the species level. In: Conservation Biology: The Theory and Practice of Nature Conservation (ed P Fielder & S Jain). Chapman and Hall, New York, 65-88.

Rab M A 1994 Changes in physical properties of a soil associated with logging of *Eucalyptus regnans* forest in southeastern Australia. Forest Ecology and Management 70:215-229.

Richardson D M, Williams P A & Hobbs R J 1994 Pine invasions in the Southern Hemisphere: determinants of spread and invasibility. Journal of Biogeography 21:511-527.

Roberts N 1994 The global environmental future. In: The Changing Global Environment (ed N Roberts). Blackwell, Oxford, 3-21.

Salwasser H, MacCleary D W & Snellgrove T A 1993 An ecosystem perspective on sustainable forestry and new directions for the U.S. National Forest system. In: Defining Sustainable Forestry (ed G H Aplet, N Johnson, J T Olson & V A Sample). Island Press, Washington DC, 44-89.

Sample V A, Johnson N, Aplet G H & Olson J T 1993 Introduction. Defining Sustainable Forestry. In: Defining Sustainable Forestry (ed G H Aplet, N Johnson, J T Olson & V A Sample). Island Press, Washington DC, 3-15.

Saunders D A, Hobbs R J & Margules C R 1991 Biological consequences of ecosystem fragmentation: a review. Conservation Biology 5:18-32.

Schofield N J, Stoneman G L & Loh I C 1989 Hydrology of the jarrah forest. In: The Jarrah Forest: A Complex Mediterranean Ecosystem (ed B Dell, J J Havel & N Malajczuk). Kluwer, Dordrecht, 179-201.

Stoneman G L 1993 Hydrological response to thinning a small jarrah (*Eucalyptus marginata*) forest catchment. Journal of Hydrology 150:393-407.

Taylor R J 1991 Fauna Conservation in Production Forests in Tasmania. Forestry Commission, Hobart.

Taylor R J & Haseler M E 1995 Effects of partial logging systems on bird assemblages in Tasmania. Forest Ecology and Management 72:131-149.

Tingay A 1985 Contemporary views of the voluntary conservation movement on the use of fuel reduction burns as a land management technique. In: Fire Ecology and Management in Western Australian Ecosystems (ed J W Ford). WAIT Environmental Studies Group, Perth, 215-218.

Underwood R J, Sneeuwjagt R J & Styles H G 1985 The contribution of prescribed burning to forest fire control in Western Australia. In: Fire Ecology and Management in Western Australian Ecosystems (ed J W Ford). WAIT Environmental Studies Group, Perth, 153-170.

Waring R H & Schlesinger W H 1985 Forest Ecosystems: Concepts and Management. Academic Press, New York.

Williams J E & Gill A M 1995 The impact of fire regimes on native forests in Eastern New South Wales. New South Wales National Parks and Wildlife Service, Hurtsville, NSW.

Withers P C, Cowling W A & Wills R T 1994 Plant Diseases in Ecosystems; Threats and Impacts in South-western Australia. Journal of the Royal Society of Western Australia Volume 77(4). Perth, Royal Society of Western Australia.

Wood W E 1924 Increase of salt in soil and streams following destruction of native vegetation. Journal of the Royal Society of Western Australia 10:35-47.